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e-MERLIN

Star-formation: The role of high resolution Radio Surveys

(an observers perspective)

Rob Beswick (JBCA/e-MERLIN/University of Manchester)

Tom Muxlow (JBCA) + contribuitions from e-MERLIN legacy teams (e-MERGE, LeMMINGs, LIRGI etc)

Outline:

- Why is high resolution important?
- Star-formation in the local Universe
  - Case studies example at high resolution
- Star-forming galaxies in deep fields
  - unique aspects revealed by high resolution

Science aims:
(Motivation1)

- Star-formation and accretion physical processes dominate appearance of galaxies and hence the Universe.
  - SF is a driving force galaxy evolution
  - Accretion provides the other a major power source contributing on a range of mass scales (stellar to SMBH)
  - Globally: Radio (both/& thermal & synchrotron) provide a sensitive and unobscured view of these processes.

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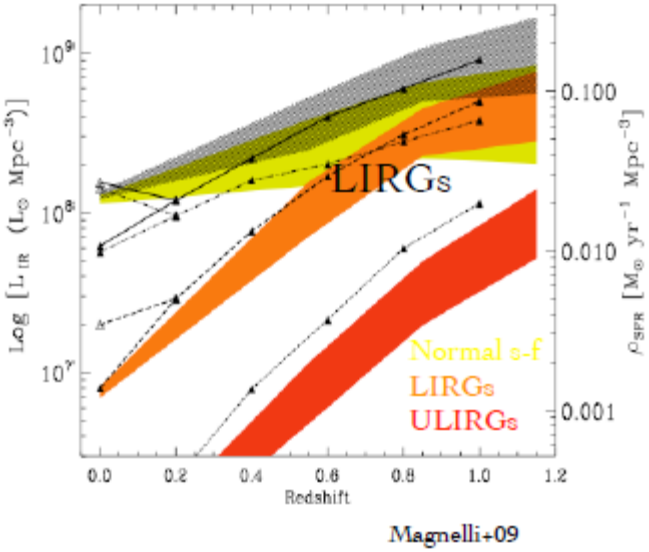
Why at radio wavelengths? Why at high resolution?

- Radio wavelengths provide an unobscured view of SF processes
- ~20% local SF on Starburst regions (Bothwell+10) – often obscured at other wavelengths
- High-resolution :
  - Locally resolve individual SF regions/components
  - Distant galaxies separate AGN/Star-formation
- In local universe resolve processes – reach galactic-style science but with statistical samples covering full gambit of environments
- Distant Universe – uncontaminated/unobscured view of SF



LIRGs and ULIRGs dominate the SFR density at increased redshift - Chary & Elbaz 2001; Le Floc'h et al. 2005

In nearby Universe?
(motivation 2)

- Ability to study detailed processes ➔ understand physics
- Covers wide range of environments - galaxy types, metallicities, evolutionary states….

- Sensitive to low luminosity sources
- Resolution to discriminate physical mechanisms within galaxies and individual sources
  - Disentangle physics
  - Resolve individual sources
    - samples of hundreds of galaxies result in samples of thousands of individual sources

- Bridge between galactic 'object-based' science and galaxy scales observations on statistical samples
- Inform high-z studies by understanding nearby galaxy analogs

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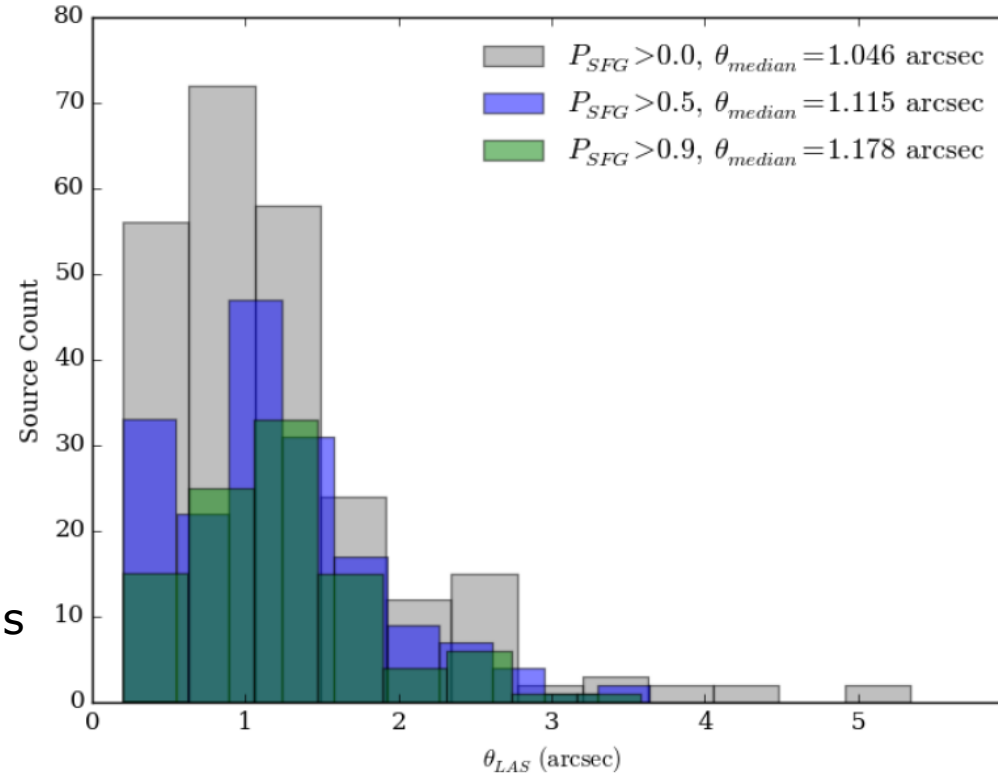
In Distant Universe?
(motivation 2)

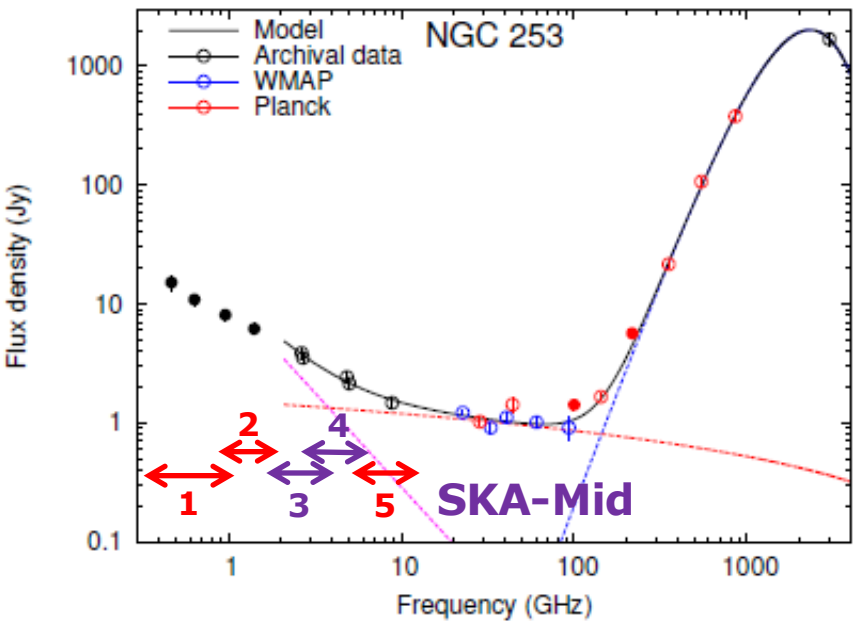
- High resolution (<0.5arcsec) critical for component separation
- **Typical galaxy** angular size of μJy starformers ~1-1.2arcsec

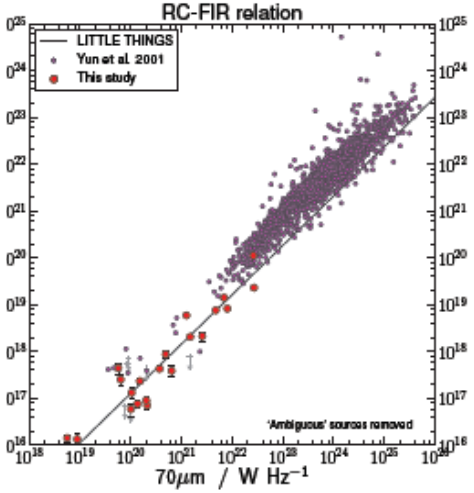


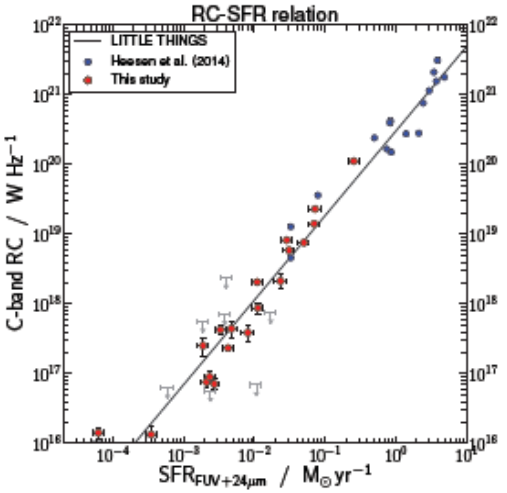
GOODS-N (e-MERLIN - 250 sources Above local 5-sigma 10-20uJy separated by starburst/AGN contribution – Wrigley 2015)

- Resolution to localise source, separate emission mechanisms
- Remove AGN contributions → derive unobscured view of SFH
- Informed by our understanding nearby galaxy analogs

Globally radio spectrum & SFR



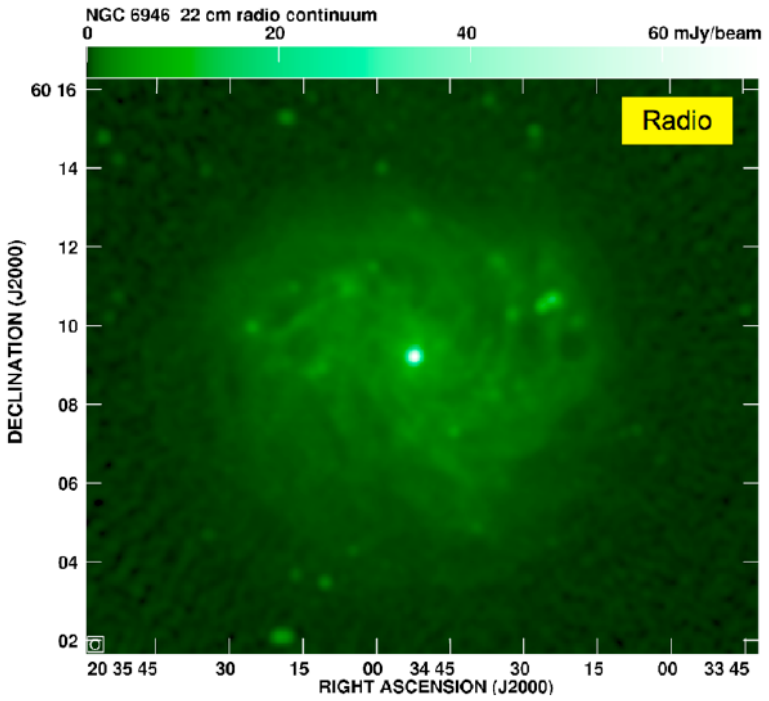


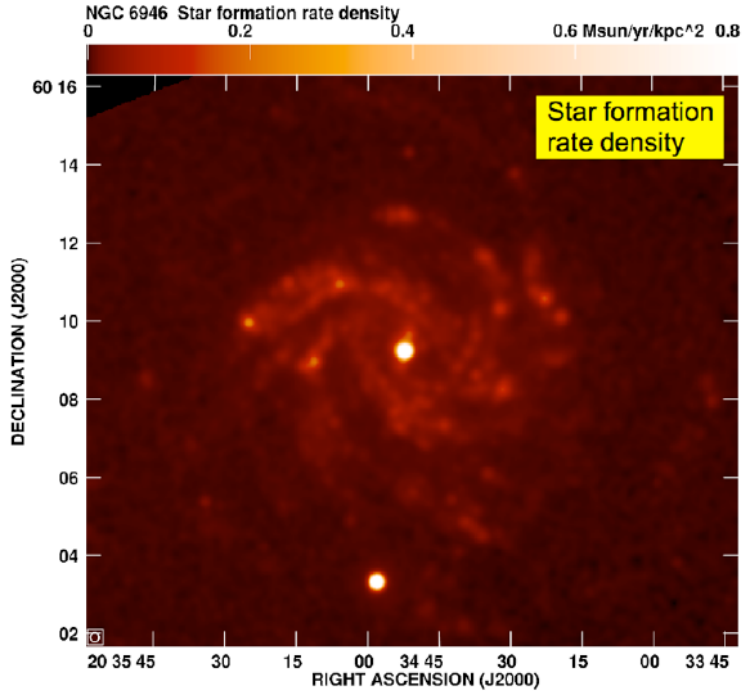


(Kitchener et al)

- thermal RC (eg at 33GHz; Murphy et al. 2012) is a virtually extinction-free proxy for the SFR, but at T~10^4K is relatively weak
- Separation of thermal/non-thermal requires good frequency coverage
- Global synchrotron correlated with IR & SFR
- SKA bands (below 5) dominated by non-thermal

Star-formation rates





- Globally & locally radio emission well correlated with IR and SFR
- On local scales continuum provides a good SFR proxy
- Next Gen. instruments and ultimately the SKA have sensitivity able to map all local galaxies via all sky-continuum surveys at

  L-band - Dwarfs → Normal galaxies → beyond
- Chart SFR unimpeded by dust obscuration on ≤kpc scales

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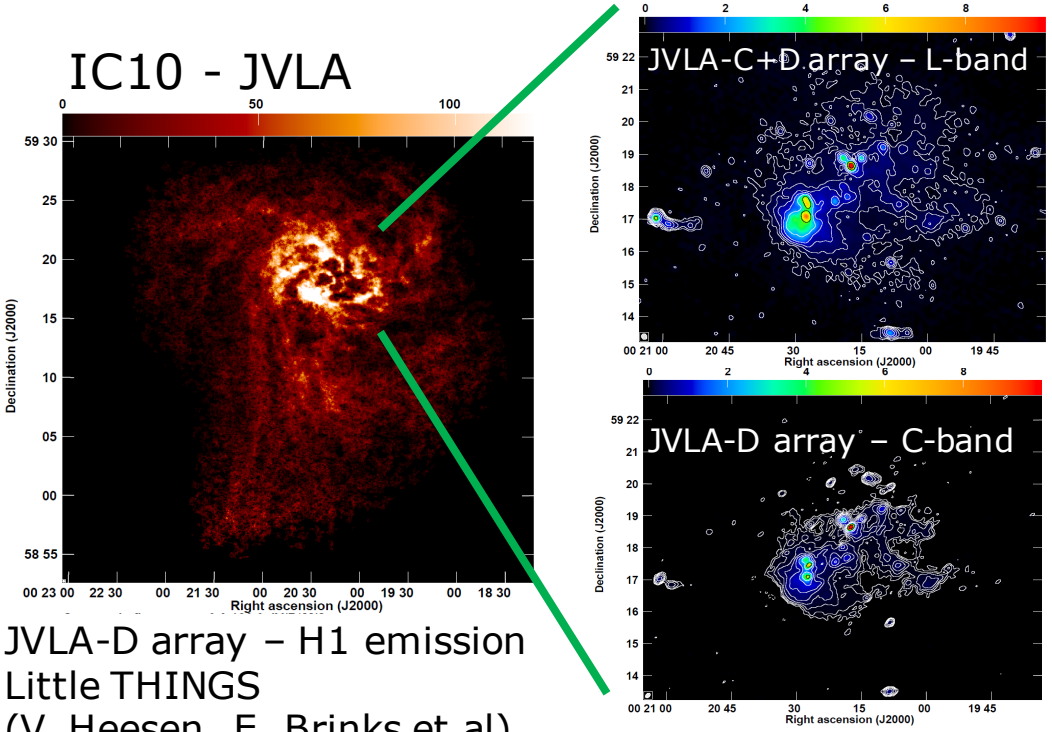
Decomposition of galaxies
(galactic-*like* astronomy in nearby galaxies)

- Via high resolution (sub-arcsec) individual sources within nearby galaxies can be catalogued and imaged – e.g. SNe, SNR, HII regions, PNe, ULXs, XRBs… etc ..
- Number counts of source ➔ direct measure of massive stare SNe rate hence SFR



JVLA-D array – H1 emission
Little THINGS
(V. Heesen, E. Brinks et al)

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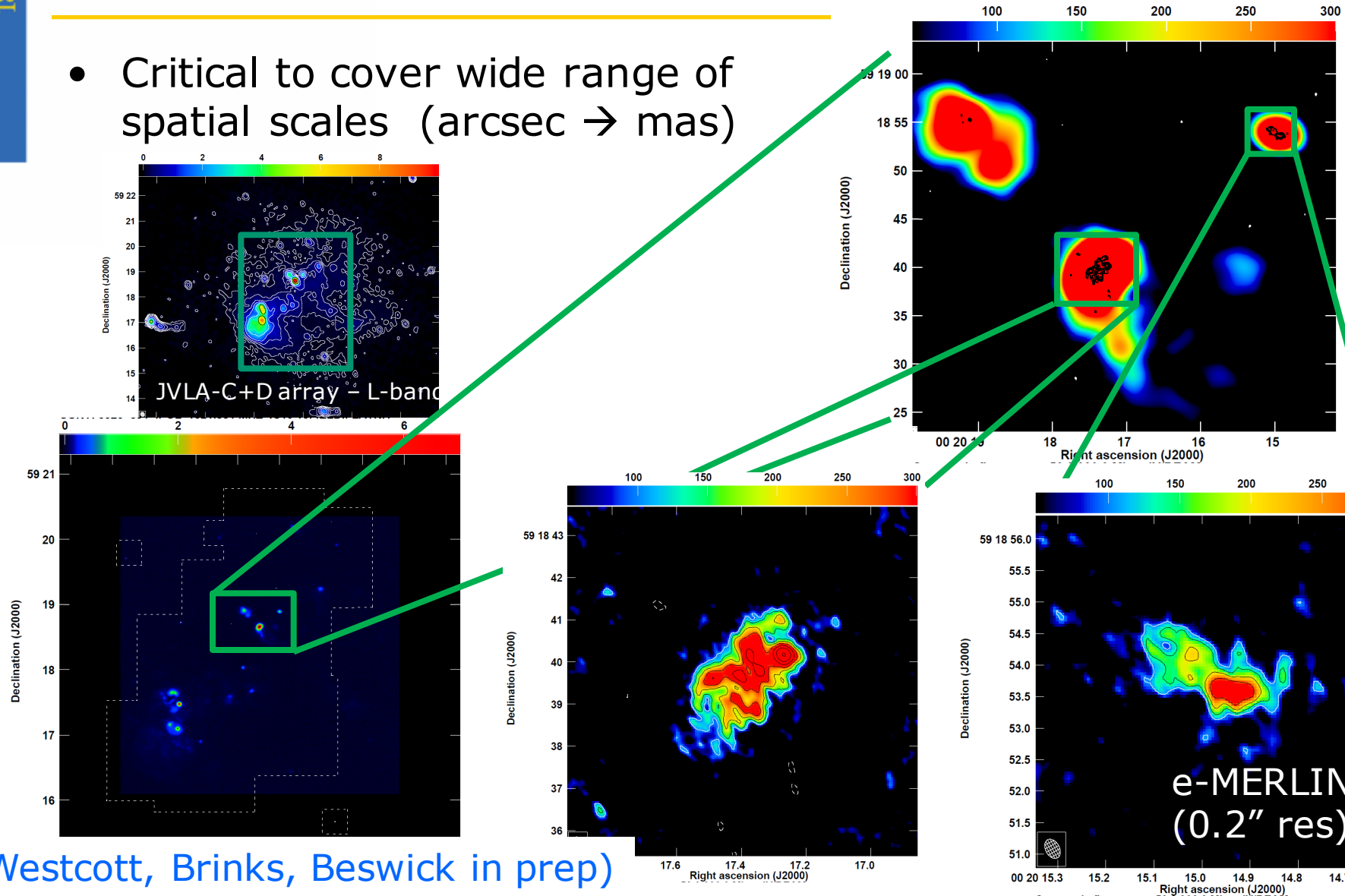
Decomposition of galaxies

- Critical to cover wide range of spatial scales (arcsec → mas)



(Westcott, Brinks, Beswick in prep)

Example of decomposition of local galaxies

- M82 – moderate, nearby starburst
- – 3.6Mpc

JVLA – (Marvel et al – NRAO PR)

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M82 SNR

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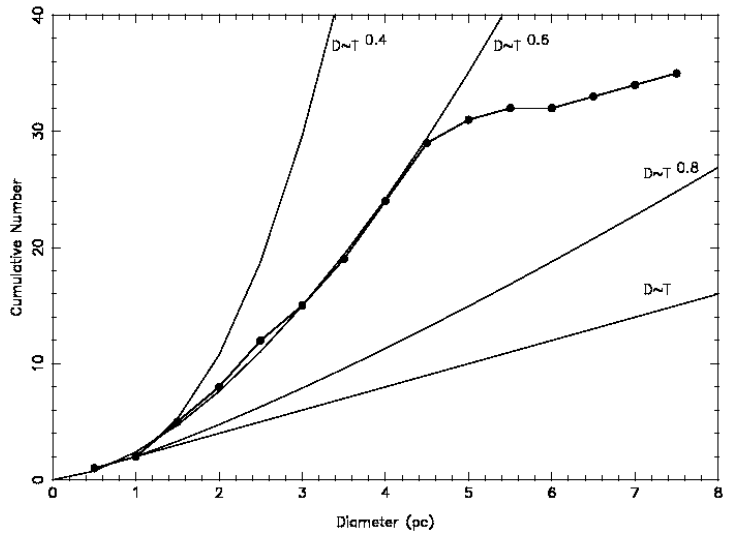
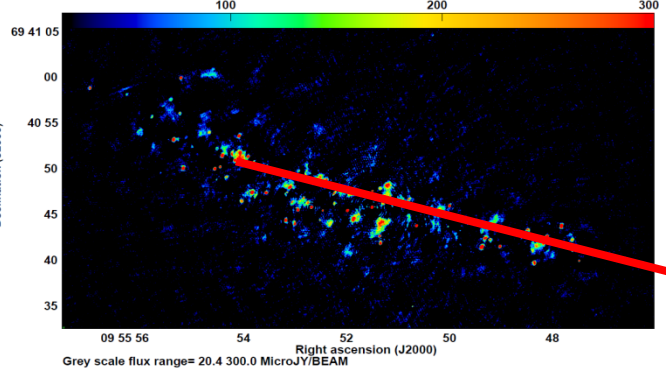
e-MERLIN/VLBI resolves all the SNR visible in M82 – derive size distribution

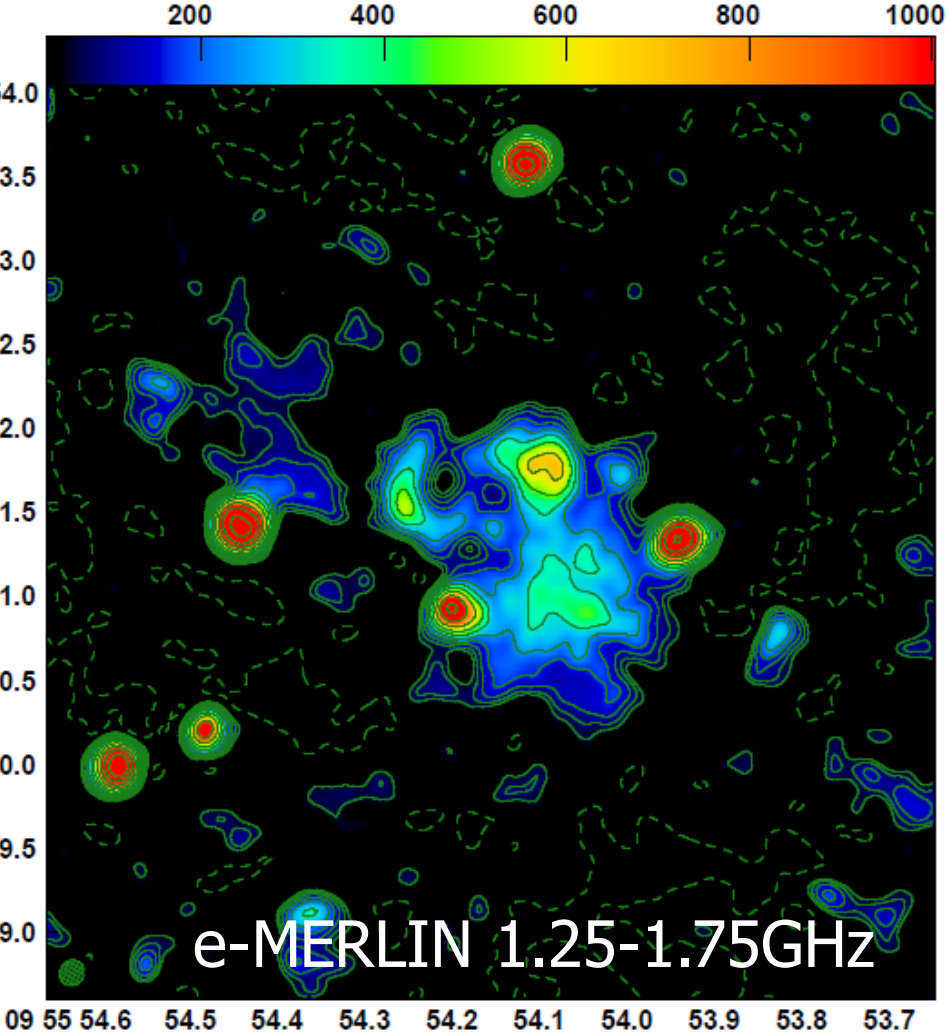
Assuming an initial expansion rate ~ 5000km/s → ages ~1000 yr with a SNR appearing every ~ 20-40 yr

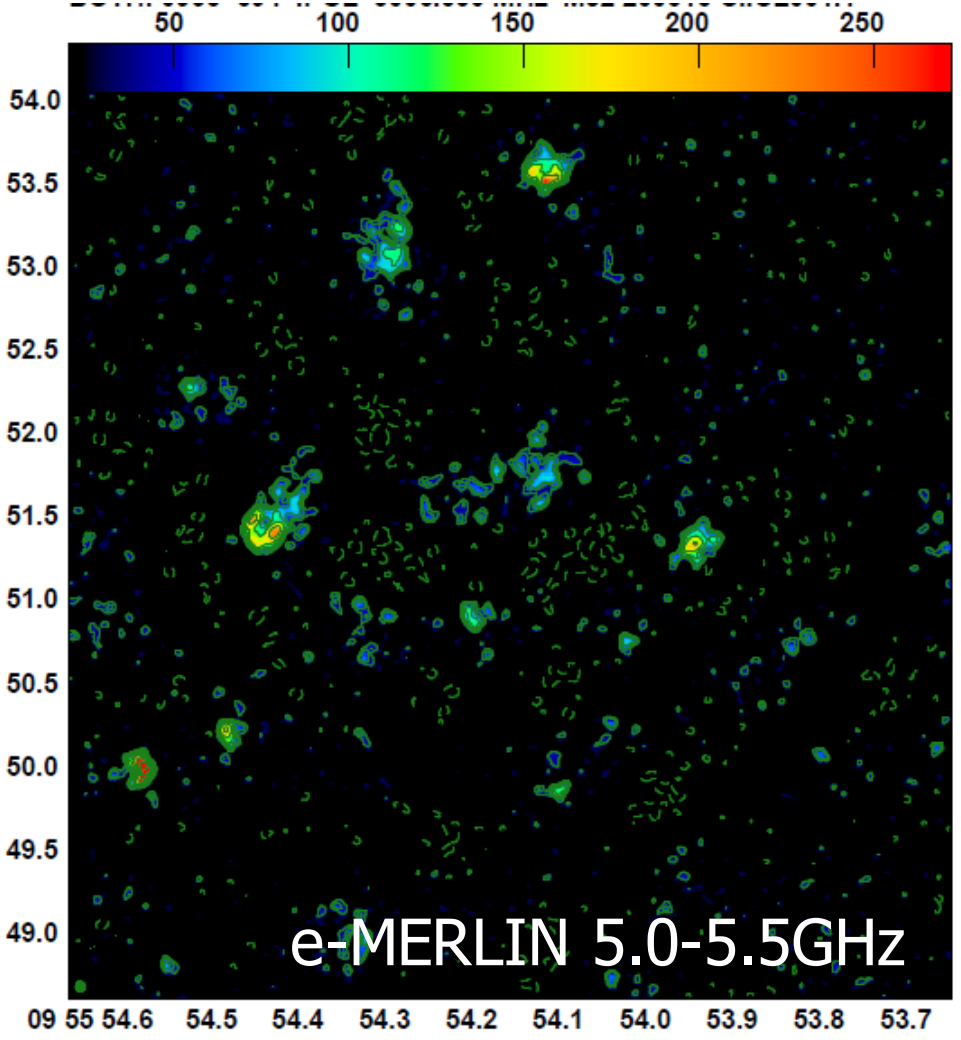


Typical expansion velocities of ~5-10,000km/s are detected by MERLIN and VLBI

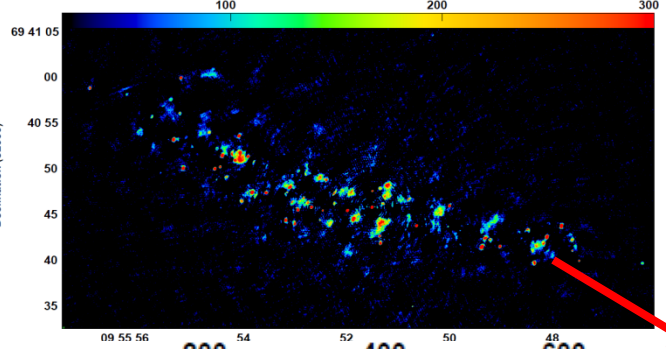
New SNR +
increasing fraction of HII regions
- Multiple SNR break-outs

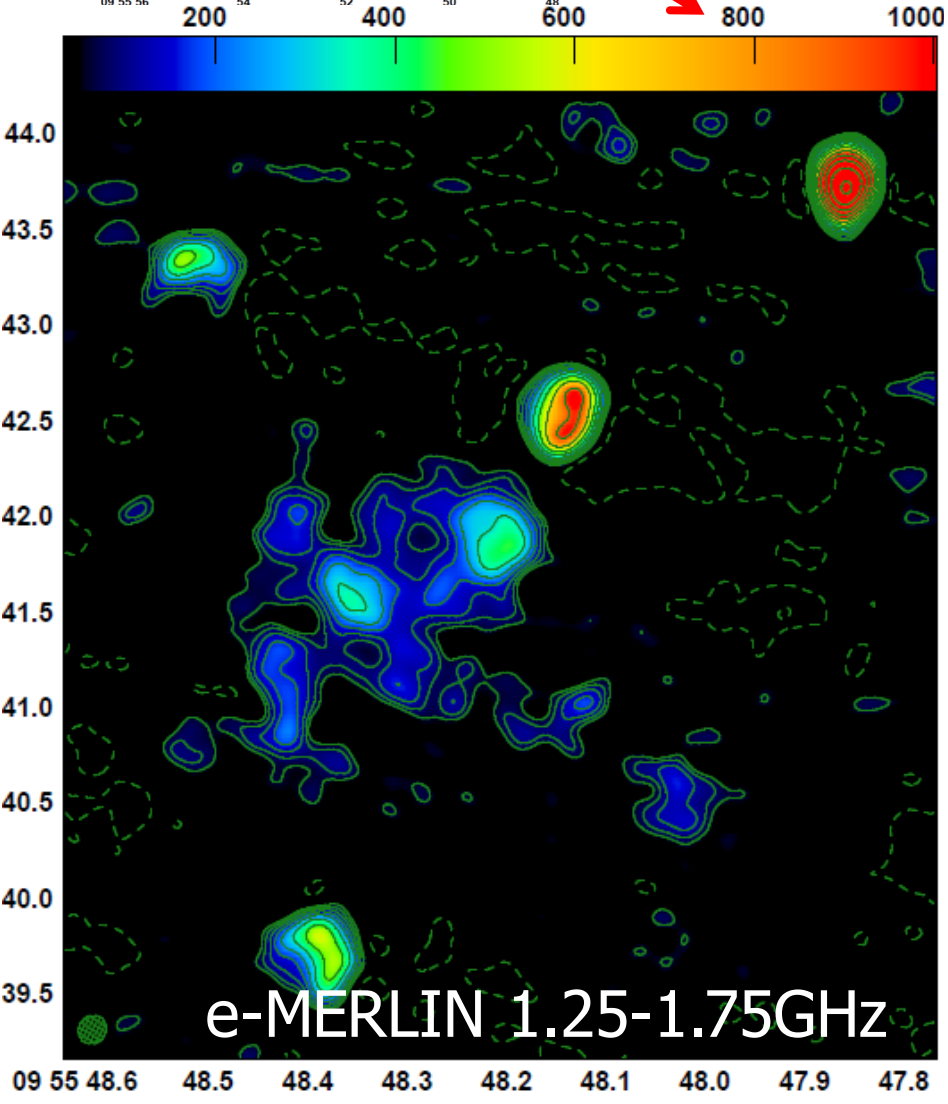


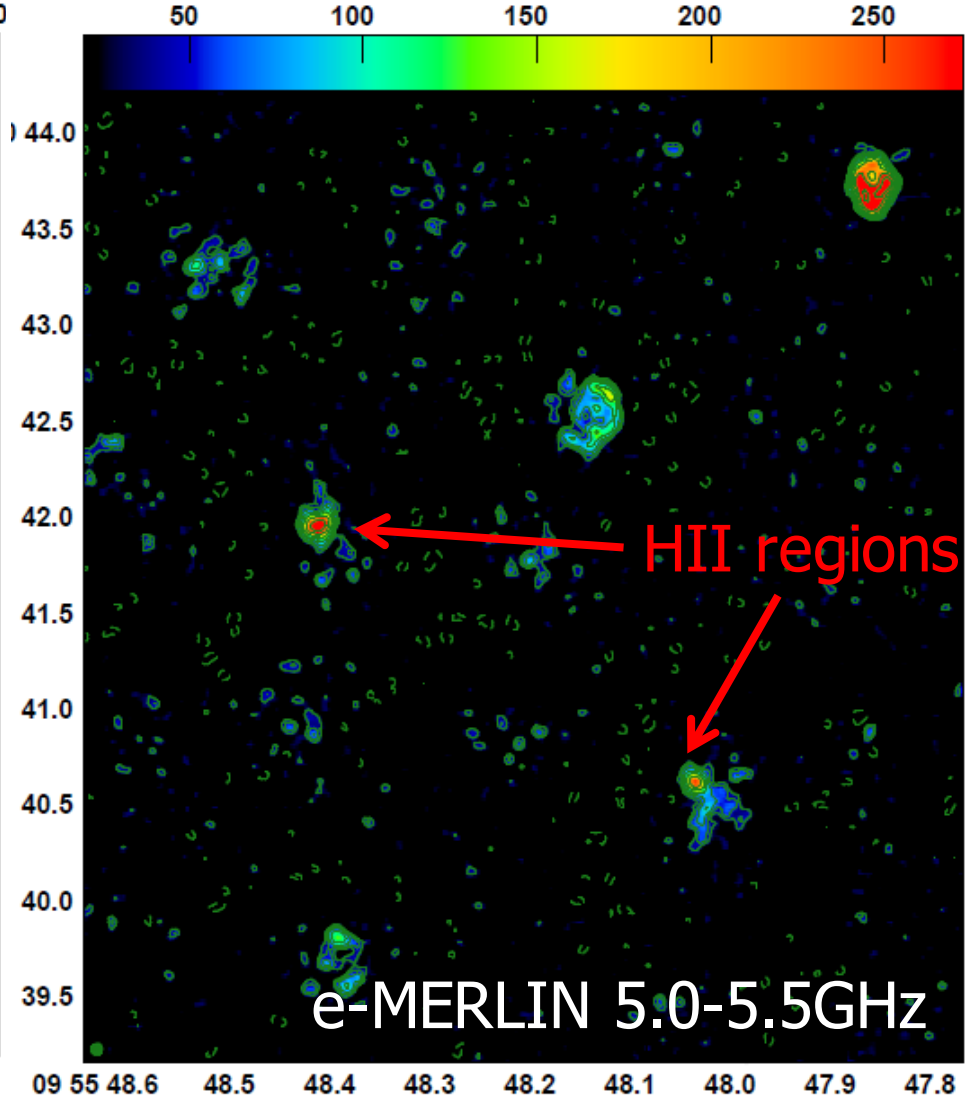




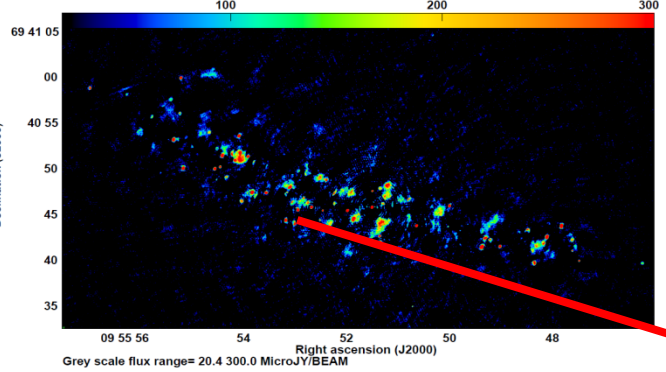
New SNR + Higher fraction of compact HII regions
- Multiple SNR break-outs – expansion into highly inhomogeneous ISM

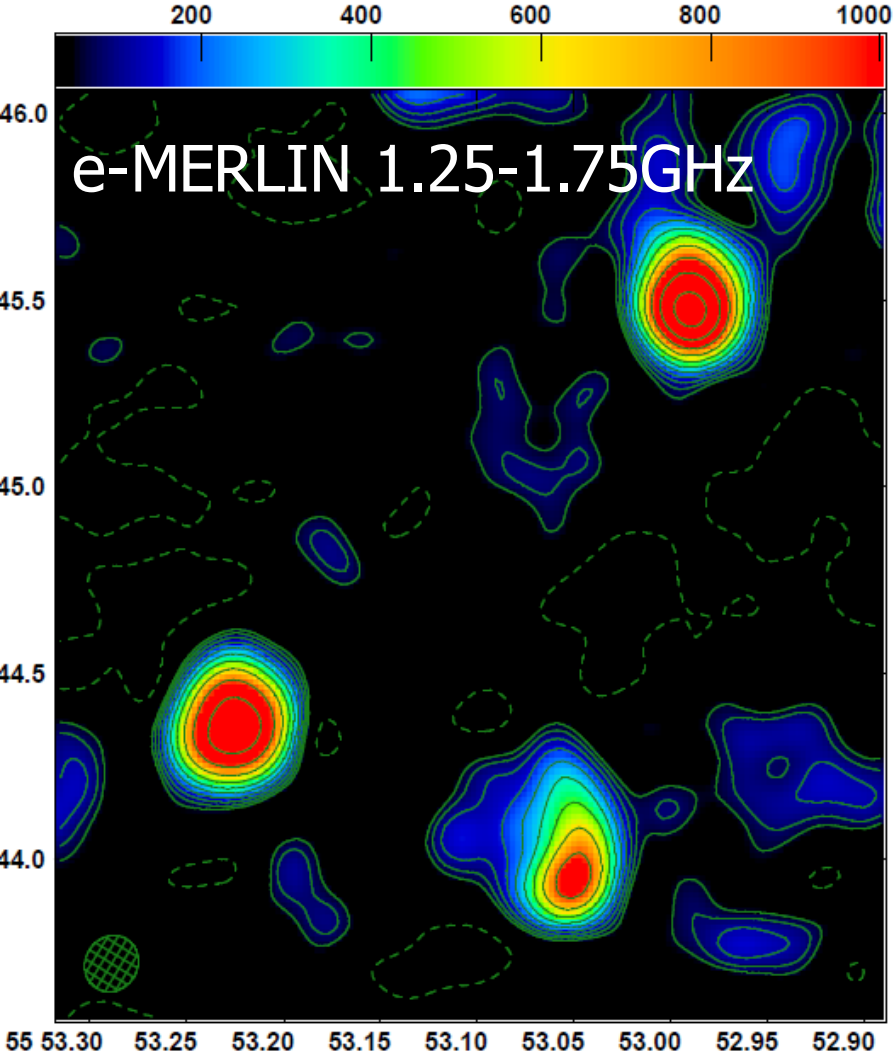


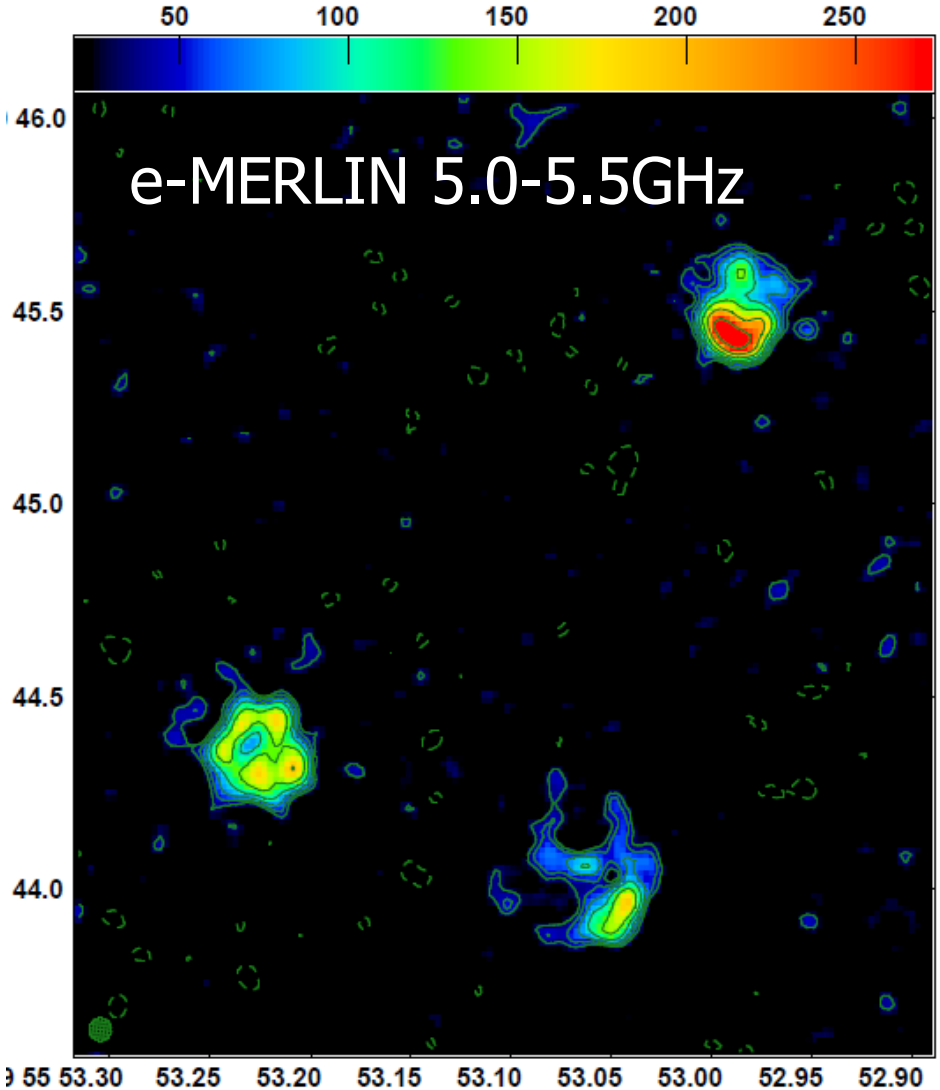


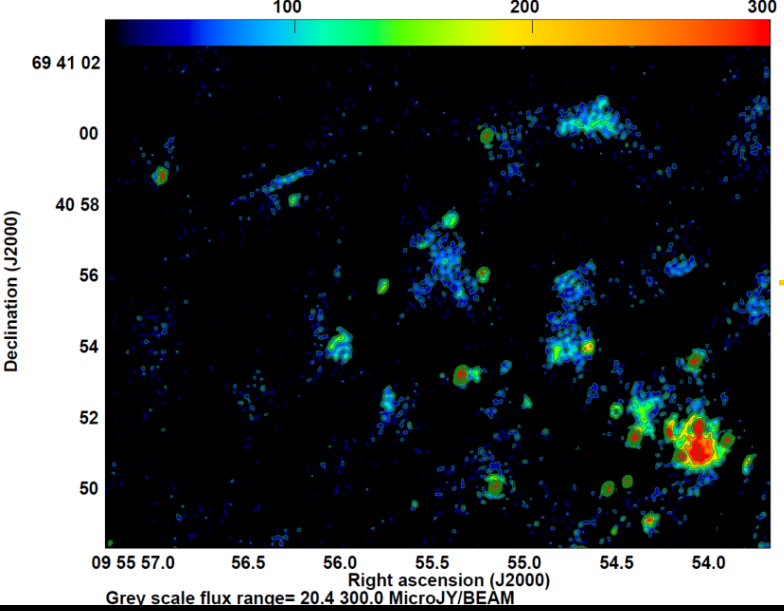


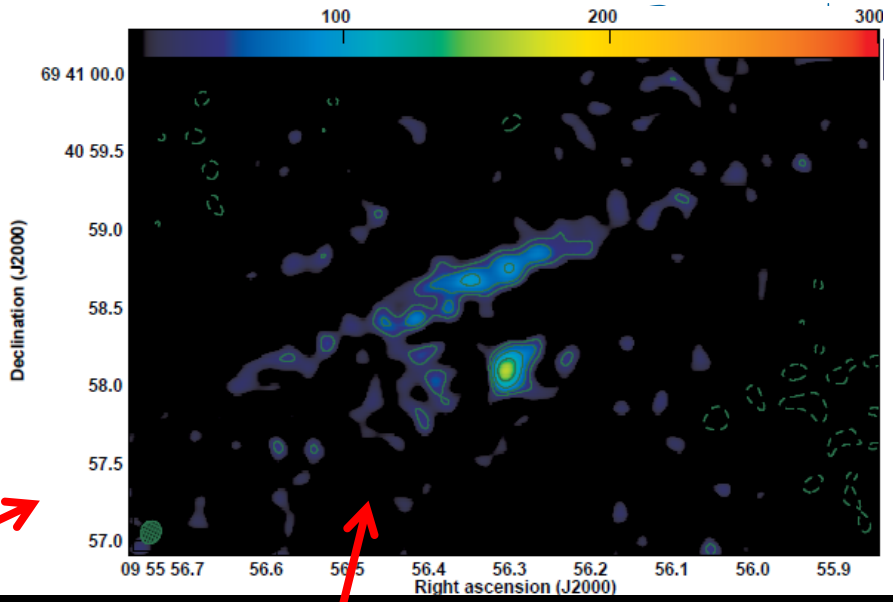
New SNR + Higher fraction of HII regions - Multiple SNR break-outs

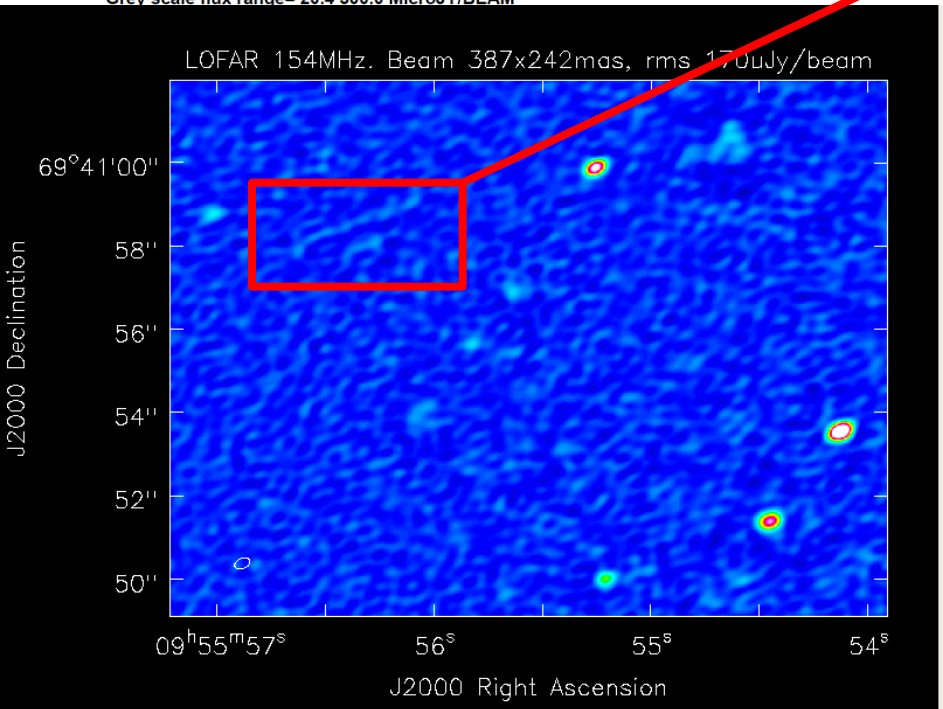




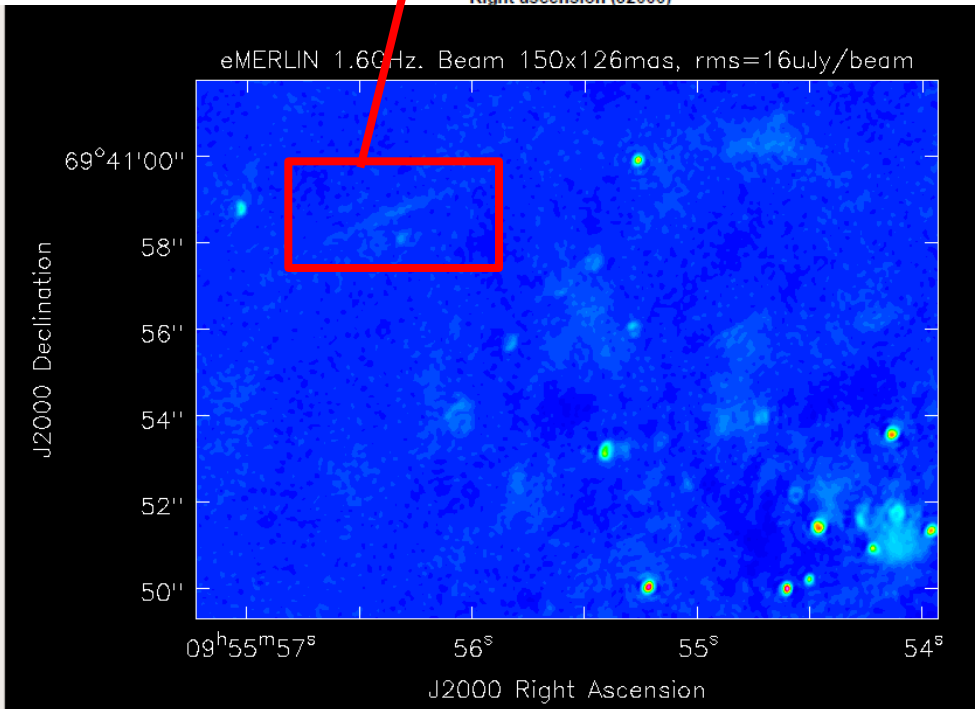








European LOFAR @ 151MHz
Varenus et al 2014



e-MERLIN @ 1.6GHz
Perez-Torres et al 2014,Beswick et al. in prep

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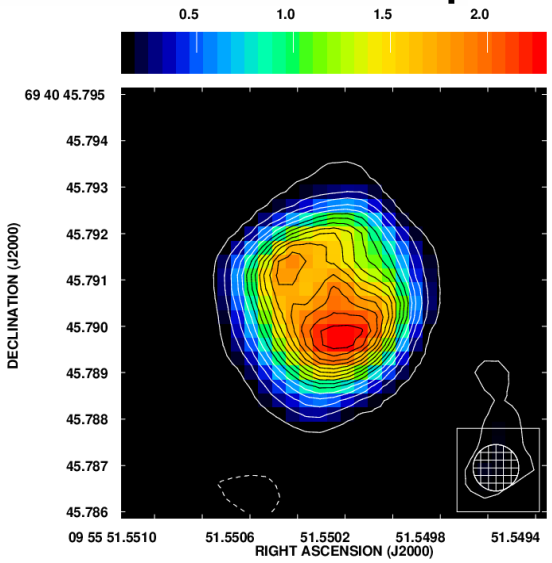
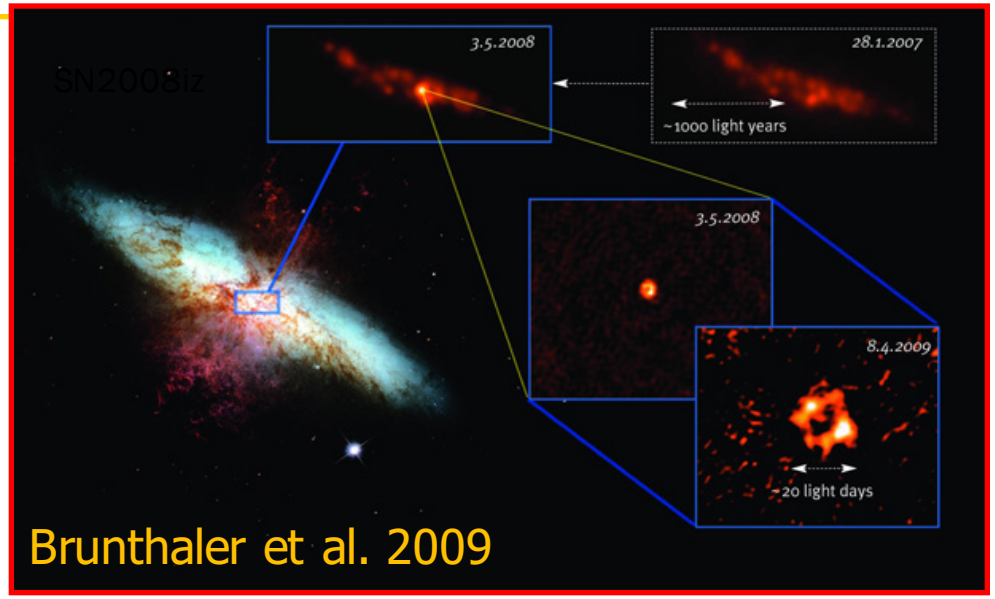
SN2008iz

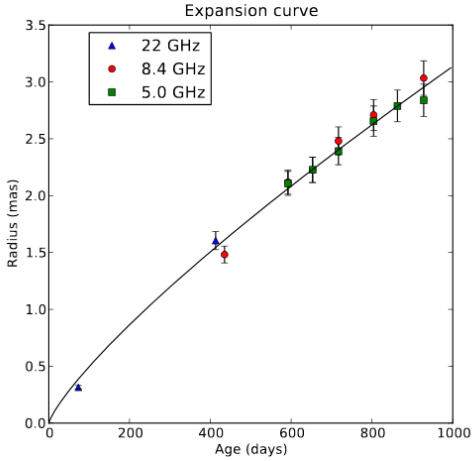
New radio supernova

Not visible in optical bands





5GHz global VLBI observations 2009



Shell-like SN expansion velocity ~21000km/s
Evidence for deceleration in 100 days (m=0.89)

→ Short free-expansion phase in high-pressure environment typical of M82

Brunthaler et al. 2010

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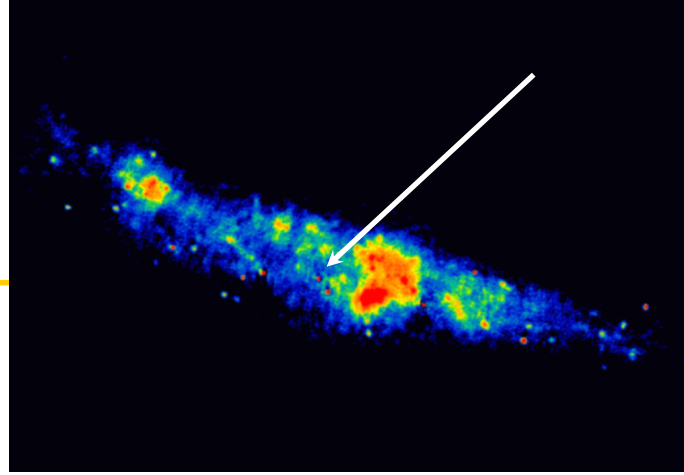
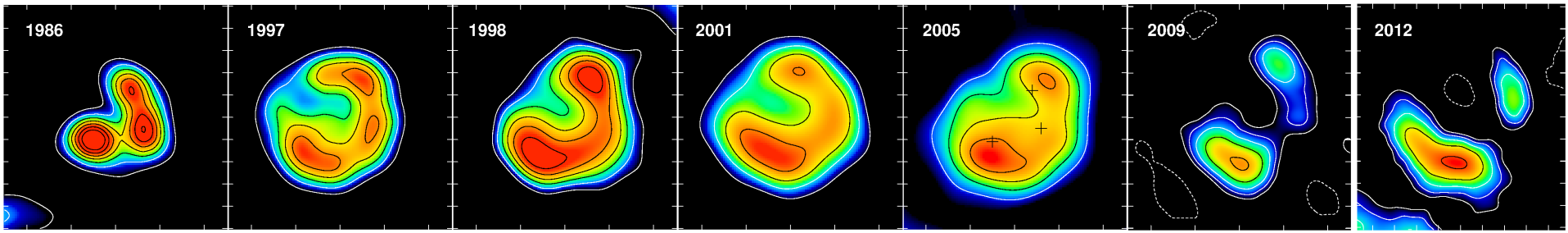
43.31+59.2



'Typical' shell-like SNR
First detected in 1972
(earlier imaging at low angular resolution)

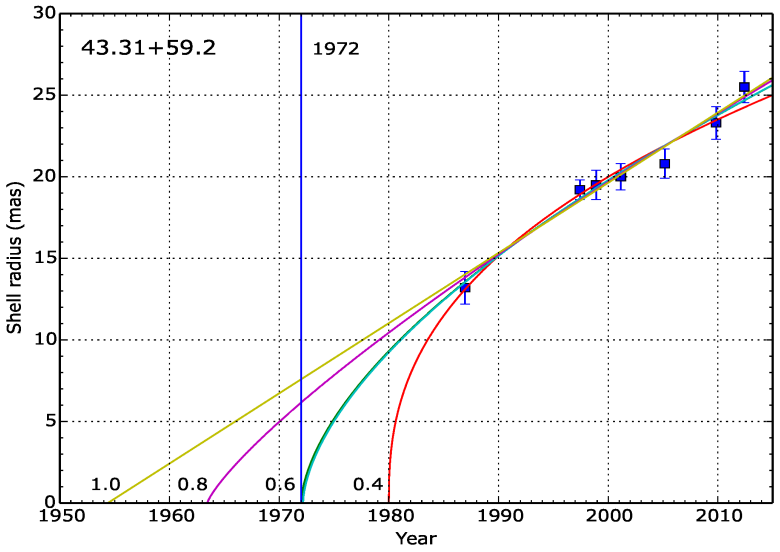
Expansion monitored over last 30 years
15 mas (~0.3pc) resolution imaging (EVN/ global VLBI)



- Expansion velocity ~ 7500-9000 kms^{-1} (Beswick et al, Fenech et al)

43.31+59.2

Monitor expansion



Expansion of SNR: $D = kt^m$
m = deceleration parameter

- Lower-limit 0.60±0.06

ISM properties?

Not yet entered Sedov phase of evolution (m=0.45)

- Can use to constrain surrounding density
  - $r_s \cong 4.1(M_{ej}/n_0)^{1/3}$
  - For M_{ej}= 0.5 ($10M_\odot$) → $n_0 \leq 250$ cm^{-3} .....Low for M82 !!

Ionised gas? Molecular clouds? Wind-blown bubble?

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Distant Universe case study

Going deep.... Going distant...

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e-MERGE Survey

A tiered e-Merlin + JVLA + EVN Legacy project
The e-MERlin Galaxy Evolution Survey

[PIs Muxlow/Smail/McHardy]

Tier 0 – *Normal galaxies out to z ~ 5*

Deep imaging around clusters to utilise amplification by lensing

2016→

Tier 1 – *Deep survey of μJy radio sources*

Deep imaging of the μJy radio sources in GOODS-N

e-MERLIN Legacy programme In progress →

Tier 2 – *Shallow-wide survey over ~2 square degrees*

2016 (?)→

→ full sampling of AGN & s-f galaxy radio luminosity function to z~5

Tier 1 - L-Band 20 days e-Merlin [~15% data reduced] +39hrs JVA-A [Complete]

C-Band 17 days e-Merlin [Q1 2016→]+19hrs JVLA-A/B/C [Complete] - mosaic

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Tier 1: New Ultra-Deep Study of GOODS-N

L-band: Single pointing centre ~20 days

Central 12' field 1σ ~ 500nJy/beam

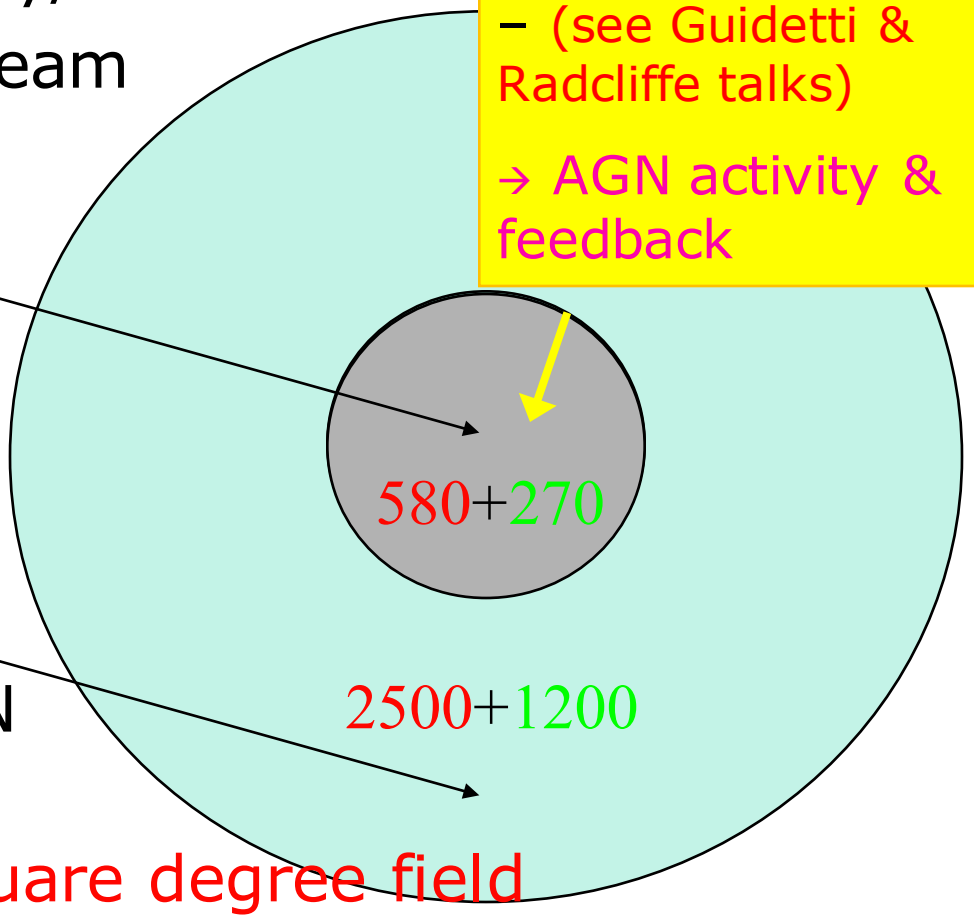
Outer 30' field 1σ ~ 1μJy/beam

Ultra-deep C-band mosaic + ultra-deep EVN L-Band – (see Guidetti & Radcliffe talks)

→ AGN activity & feedback

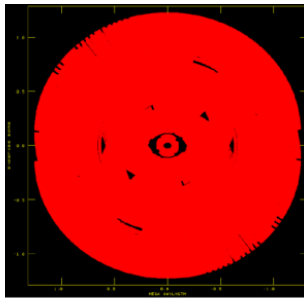
~580 starbursts and
~270 AGN – beam
~200 mas complete to
~3μJy (>10 times deeper than the 2005 study)

800 square arcmins, annulus ~2500 starbursts & ~1200 AGN complete to ~6μJy



>5000 sources in 0.2 square degree field

Tier 1: New Ultra-Deep Study of GOODS-N



e-Merlin L-band data (1.23-1.74GHz → full *uv* coverage)

→ High fidelity imaging of faint radio structures at full resolution

Initial (2015) detailed investigation of >200 SF galaxies and AGN L-Band e-MERLIN/JVLA + EG078 + C-Band JVLA mosaic 1σ~1.5μJy/bm

(Also see talks by Daria Guidetti & Jack Radcliffe tomorrow)

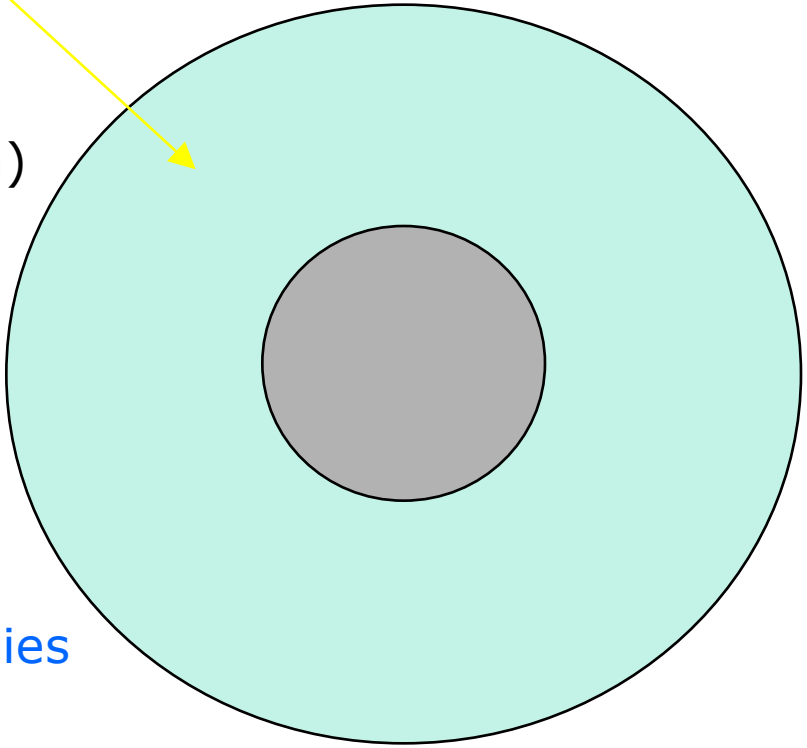
L-Band image 1σ ≤ 2μJy/bm

+EG078 EVN deep wide-field 1σ~3μJy/bm)

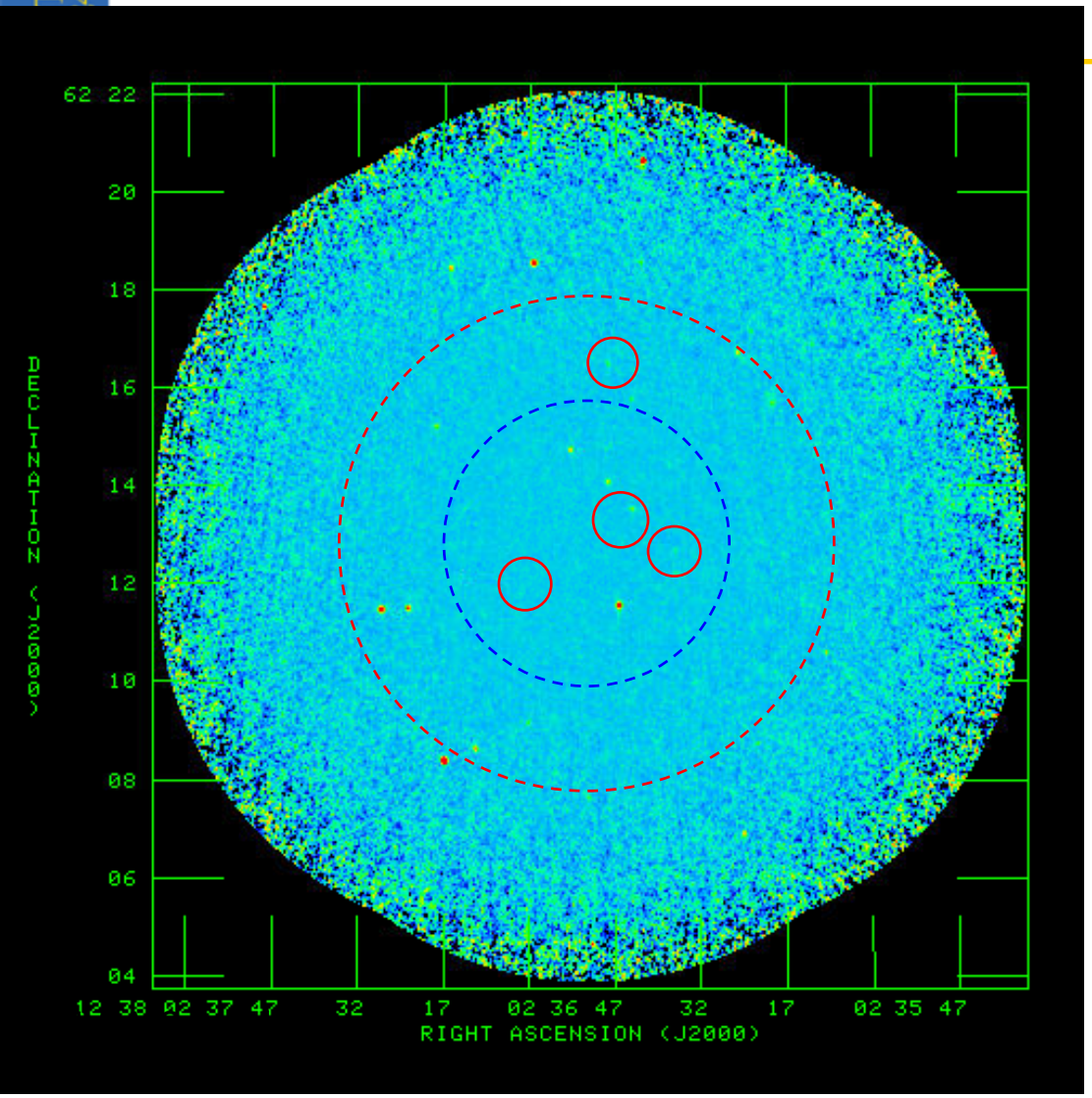
Only a few classical double structures – most AGN are small core-jets

High resolution imaging can morphologically distinguish AGN & SF

<70μJy population dominated by s-f galaxies typically at z<1.5



Tier 1: New Ultra-Deep Study of GOODS-N



Latest deep high resolution e-MERLIN images of a variety of starburst galaxies from the interim study of ~200 sources:

4 starburst examples

3 e-MERLIN datasets (~60 hrs) + archival VLA σ~2.5 μJy

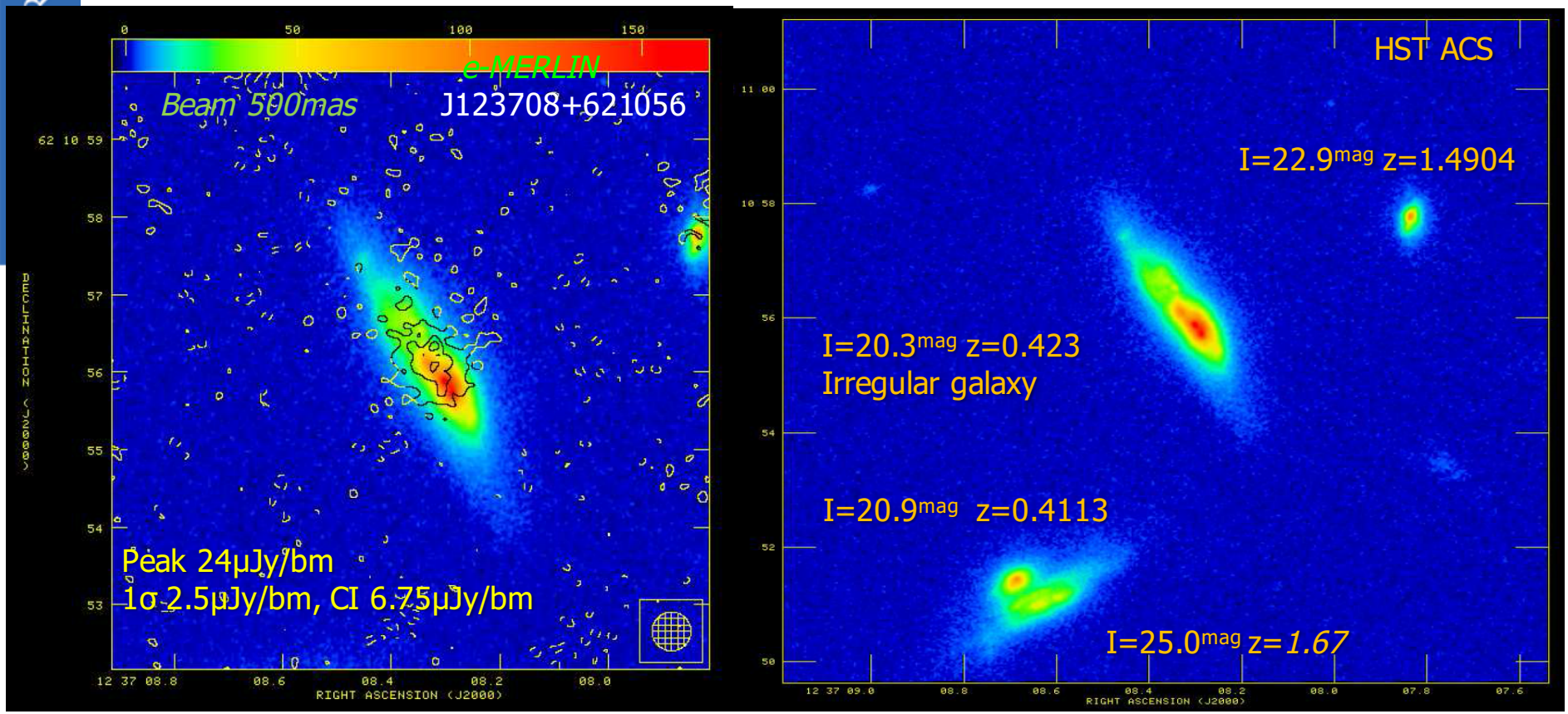
In progress:
Optimising weighting scheme for JVLA L-Band data with sub-set of e-MERLIN dataset → σ~< 2μJy

Sensitivity, Astrometry, Fidelity...

Classical starbursts – Sub-mm starbursts – Starbursts + AGN – Starbursts in mergers

Classical Starburst

GOODS-N



Extended (α>0.35) starburst ($S_{1.4}$ = 45μJy).

Radio emission from central region of 10^{10} $M_\odot$ Irregular galaxy – No compact emission detected

$L_{1.4}$ =3.8x10^{22} W/Hz

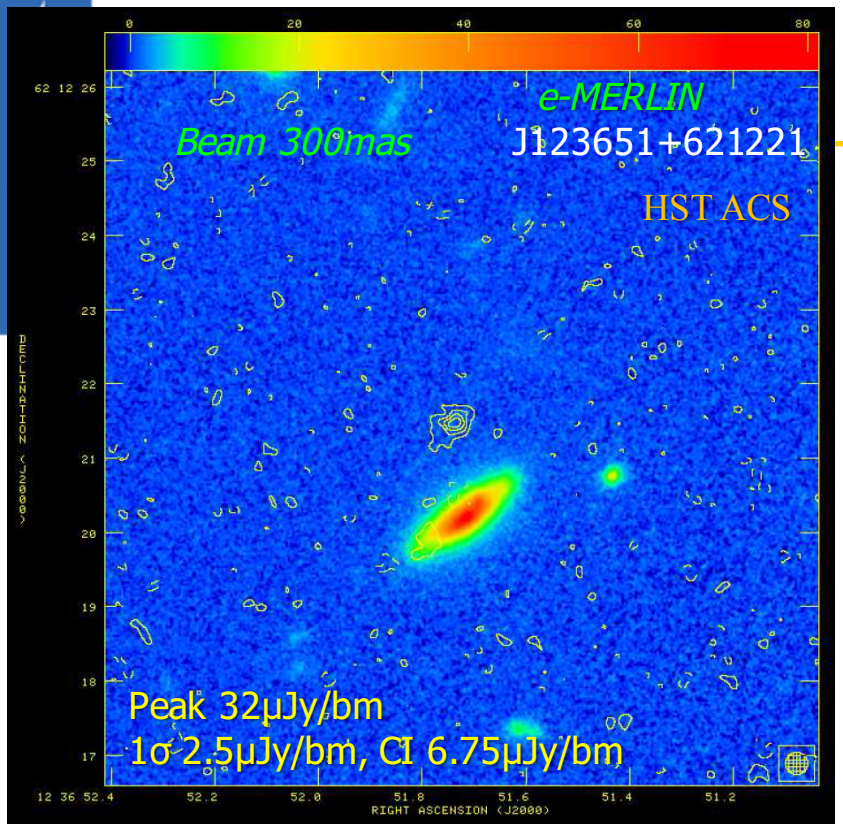
→ Star-formation rate 15 $M_\odot$/yr

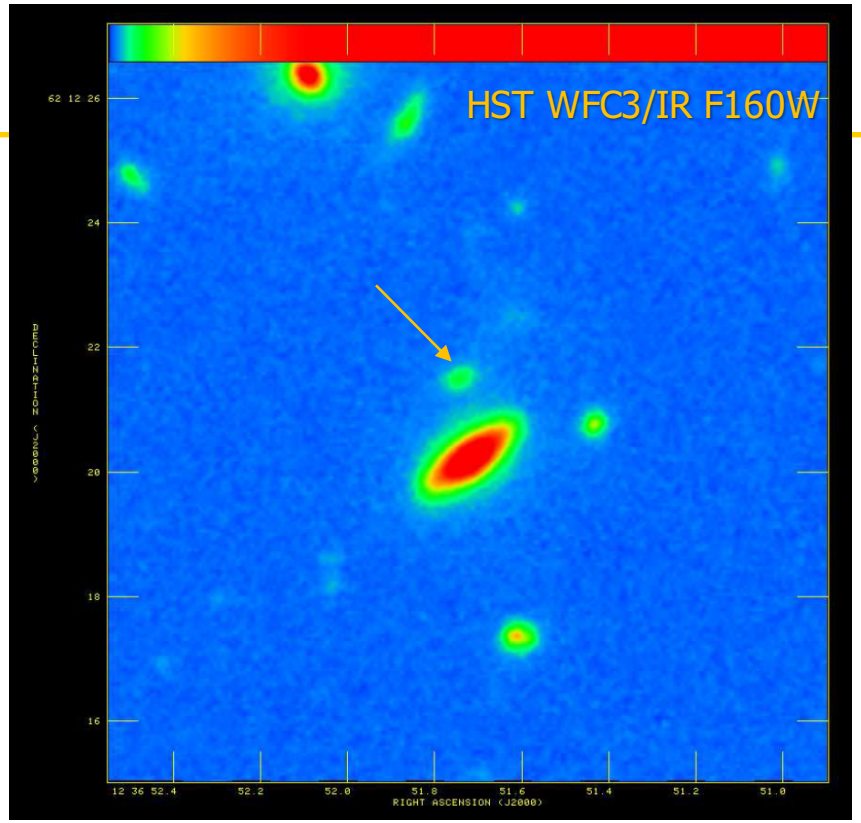
(0.1-100$M_\odot$ assuming Salpeter IMF)

Extended (1.2") starburst – Central region shows optical obscuration (dust lane?)

Sub-mm Starburst

GOODS-N





Extended (0.9") steep spectrum (α>0.71) starburst ($S_{1.4}$ = 49μJy).

Radio emission lies to north of emission-line galaxy at z=0.299 – No compact emission (VLBI)

No detectable emission in visible bands.

Faint very red object detected in F160W (1.6μm IR)

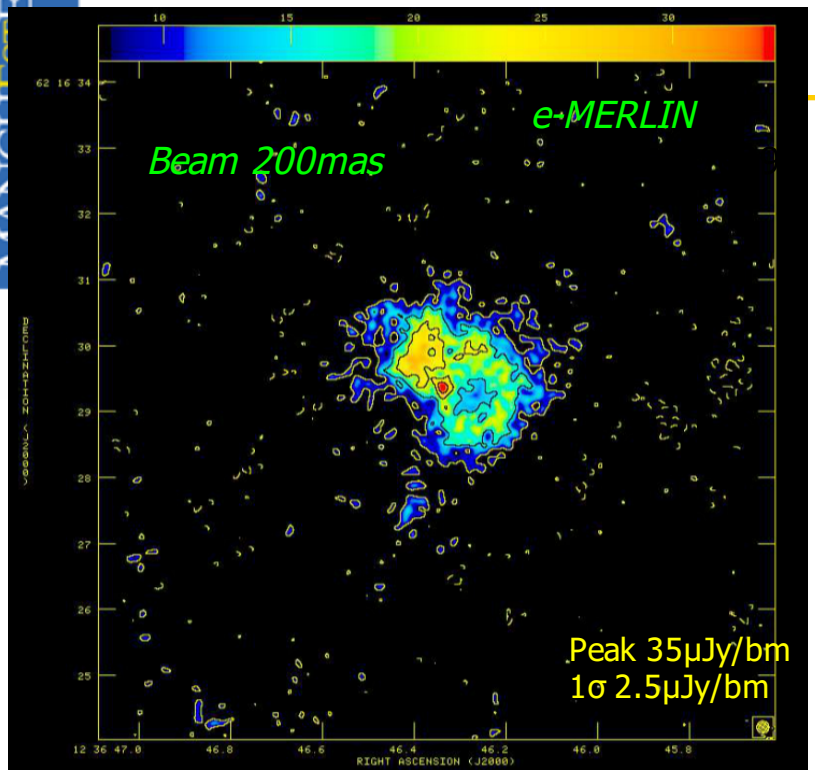
ISO detection → dust obscured starburst at z~3. SMA detection at 1.3mm

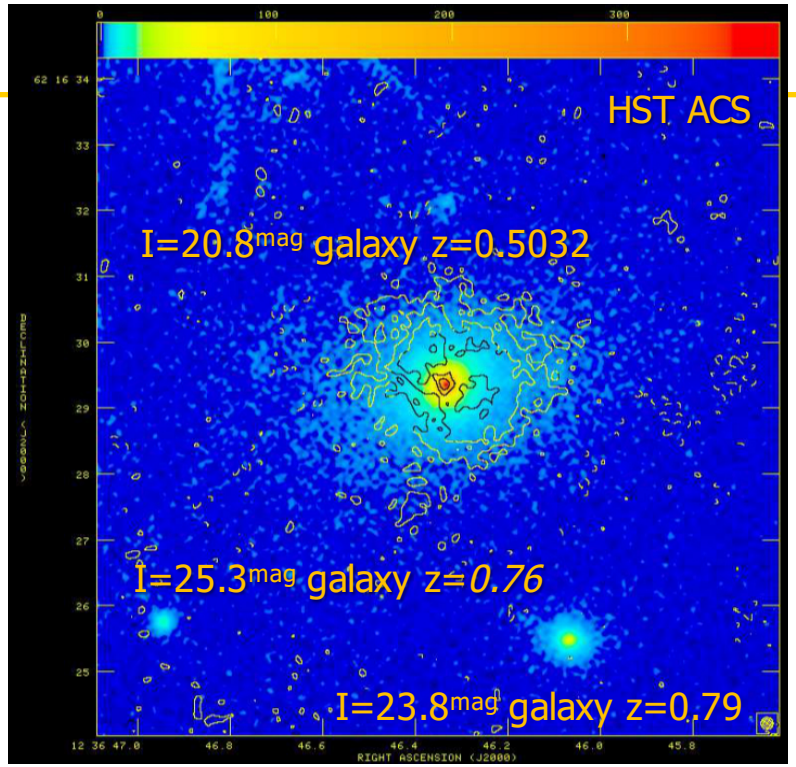
Hard Chandra X-rays → obscured QSO at z=2.7

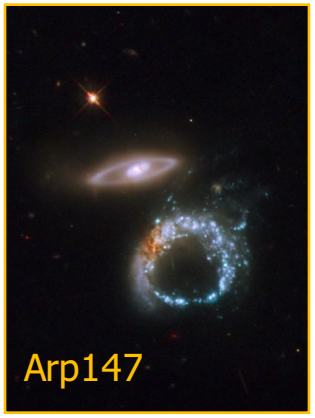
$L_{1.4}$ =8.6x10^{24} W/Hz → Star-formation rate ~2000 $M_\odot$/yr

Starburst + AGN?

GOODS-N







Extended steep-spectrum (α>1.62) starburst with embedded AGN? ($S_{1.4}$ = 393μJy). → Ring of star-formation – interacting galaxies?

Radio emission extends across face of massive spheroidal galaxy

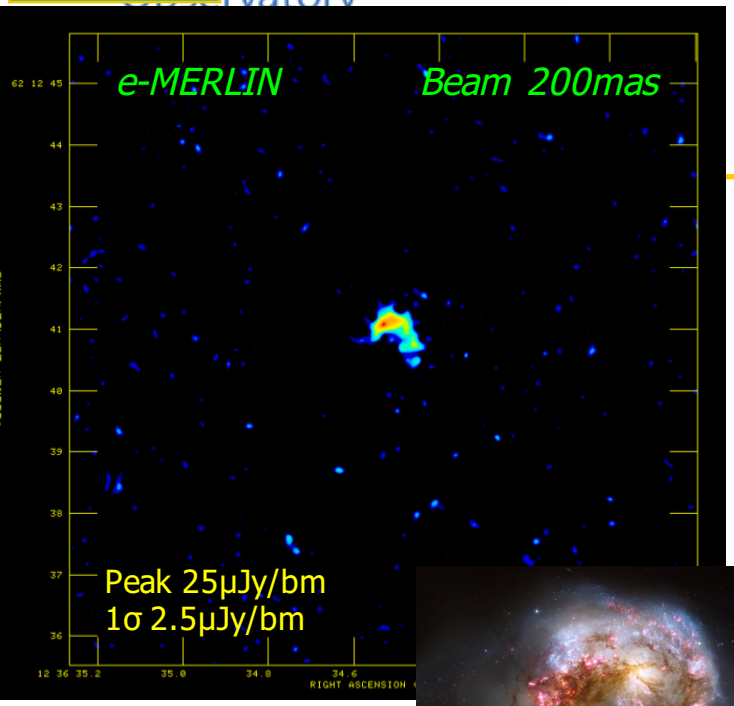
$L_{1.4}$ =8.5x10^{23} W/Hz → Star-formation rate ~200 $M_\odot$/yr

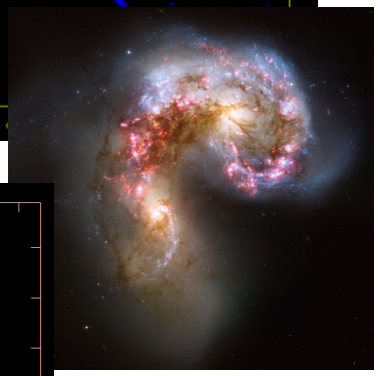
Bright galaxy core shows BL emission → Optical AGN activity

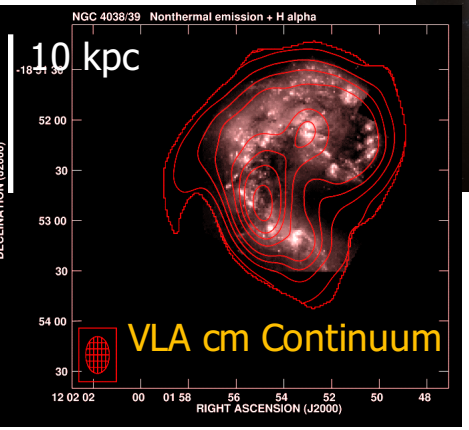
AGN or nuclear starburst? – C-Band/VLBI to look for faint radio core

Starburst in merger

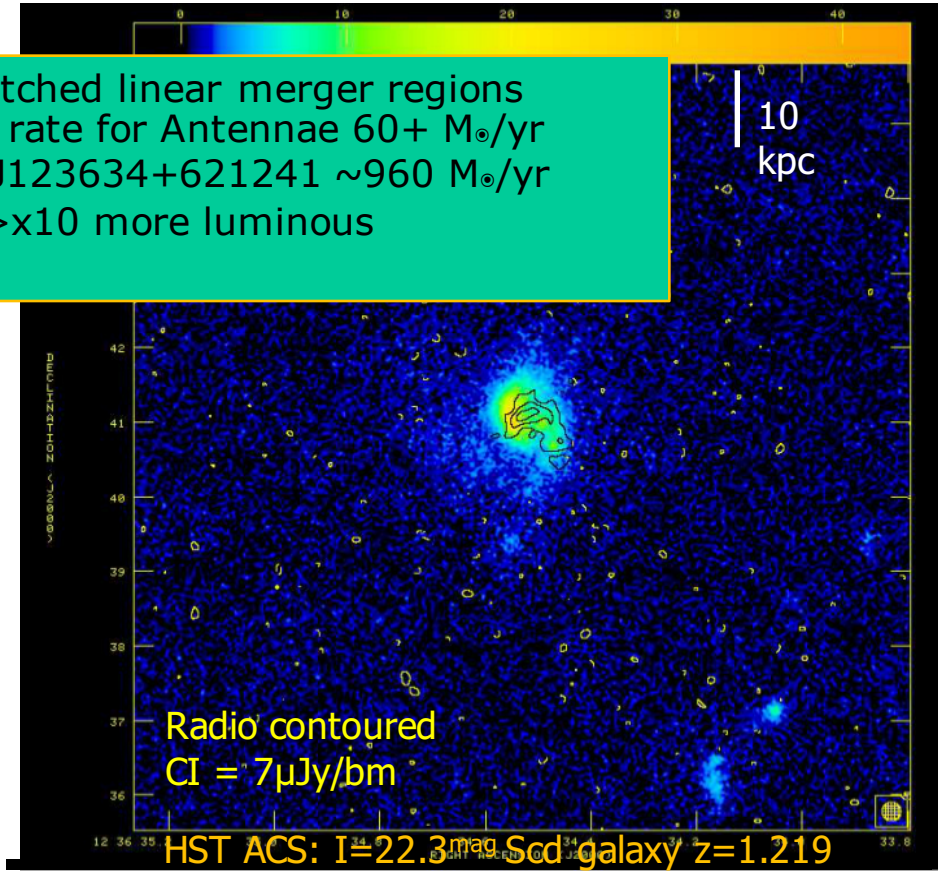
GOODS-N







~Matched linear merger regions
S-F rate for Antennae 60+ M☉/yr
cf J123634+621241 ~960 M☉/yr
→ >x10 more luminous



Steep-spectrum (α=0.74) starburst (Total 230μJy) – ISO detection

$L_{1.4}$ =4.1x10^{24} W/Hz → Star-formation rate ~960 M☉/yr

Merging Scd sub-mm galaxy with tidal tail

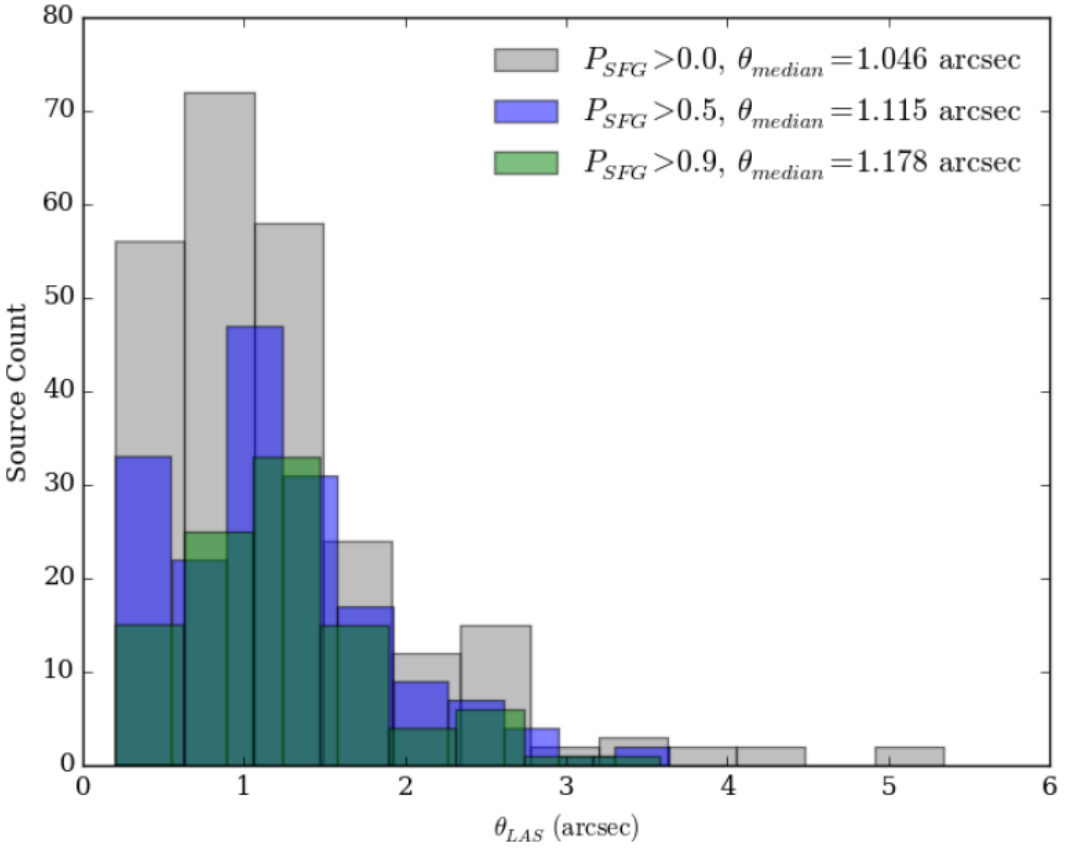
– Radio emission follows merger & extends towards tail (cf 'Antennae')

Resolved μJy radio source population - continuum

- High resolution (<0.5arcsec) critical for component separation
- Typical angular size of μJy starformers

  ~1-1.2arcsec

i.e. to measure sizes and shapes need significantly sub-arcsec resolution
weak lensing population



GOODS-N (e-MERLIN - 250 sources
Above local 5-sigma 10-20uJy separated by starburst/AGN contribution – Wrigley 2015)

Summary (1)

- High resolution – unique view of star-formation processes in galaxies at all redshifts.
  - **Local Universe** → resolved studies individual SF regions, HII regions, SNe, SNRs etc
  - New sensitive telescopes (JVLA, eMERLIN, EVN, LOFAR etc etc) are completely openning the field
    - No longer limited to 'nearest or brightest'
    - Large representative samples
    - Provide a true zero-redshift view of obscured SF across all galaxy environments
  - Anchor point for our understanding in the distant Universe and to place a context for high linear resolution Galactic studies of SF.

Summary (2)

- High resolution – unique view of star-formation processes in galaxies at all redshifts.
  - **Distant Universe** → Resolve individual objects
  - New sensitive telescopes (JVLA, eMERLIN, EVN, LOFAR etc etc) openning the field (again true)
    - Many ongoing 'deep' field – but need resolution!
    - Typical angular size of (μJy) SF galaxies is ~1-1.3 arcsec. → Target population for current and future radio surveys (SKA etc)
    - Resolution is a critical diagnositic in our armoury to separate the contributions (at Radio Wavelengths) of Accretion emission (AGN) and Star-formation.
    - Required to allow Cosmic SFH to be determines (inc obscured SF)..

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